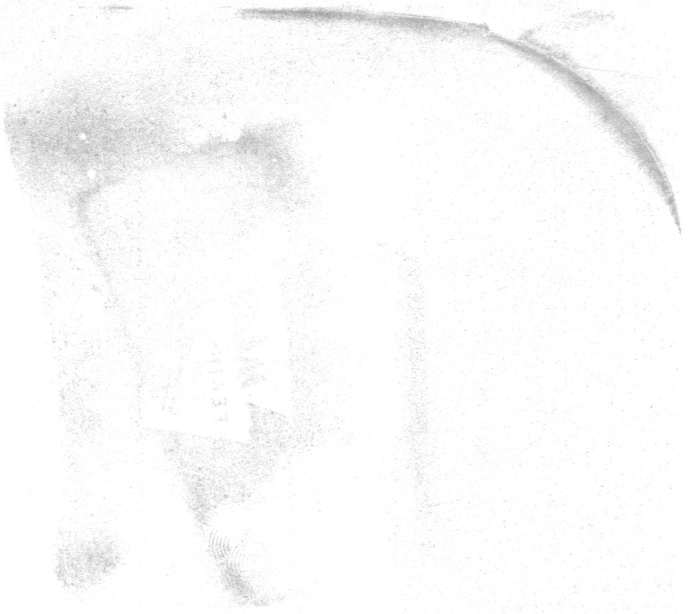
ELECTROLUMINESCENCE

by HENRY F. IVEY



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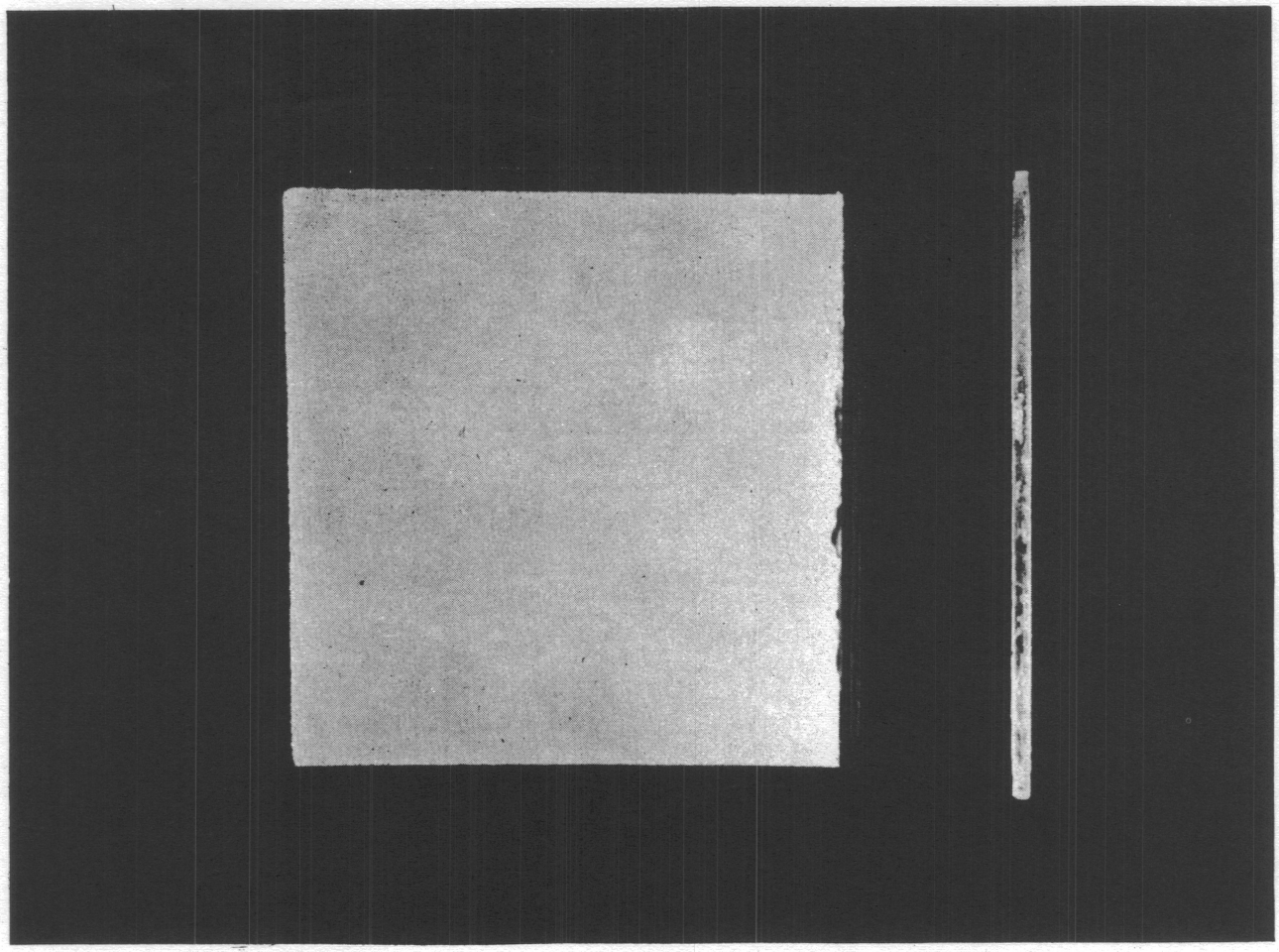
Electroluminescence

When a luminescent substance such as zinc sulfide is placed in an alternating electric field, it emits light. This effect makes possible thin illuminating panels and many other useful devices

by Henry F. Ivey

A new revolution in artificial lighting is in the making. Through most of human history man illuminated the darkness by means of a flame—progressing from the torch to the candle to the kerosene lamp. Within the last three quarters of a century our mode of living has been transformed by the incandescent and the fluorescent lamp. The innovation now under development is the luminescent panel. The prospect is that within a few years our houses and offices will begin to be lighted by luminous ceilings and walls. All sorts of attractive possibilities are opened up by this method of illumination. It will give us light of almost any color or brightness at will. Merely by turning a knob, we shall be able to bathe our rooms with rosy light on days of dreary skies, or with cool blue light when the sun is



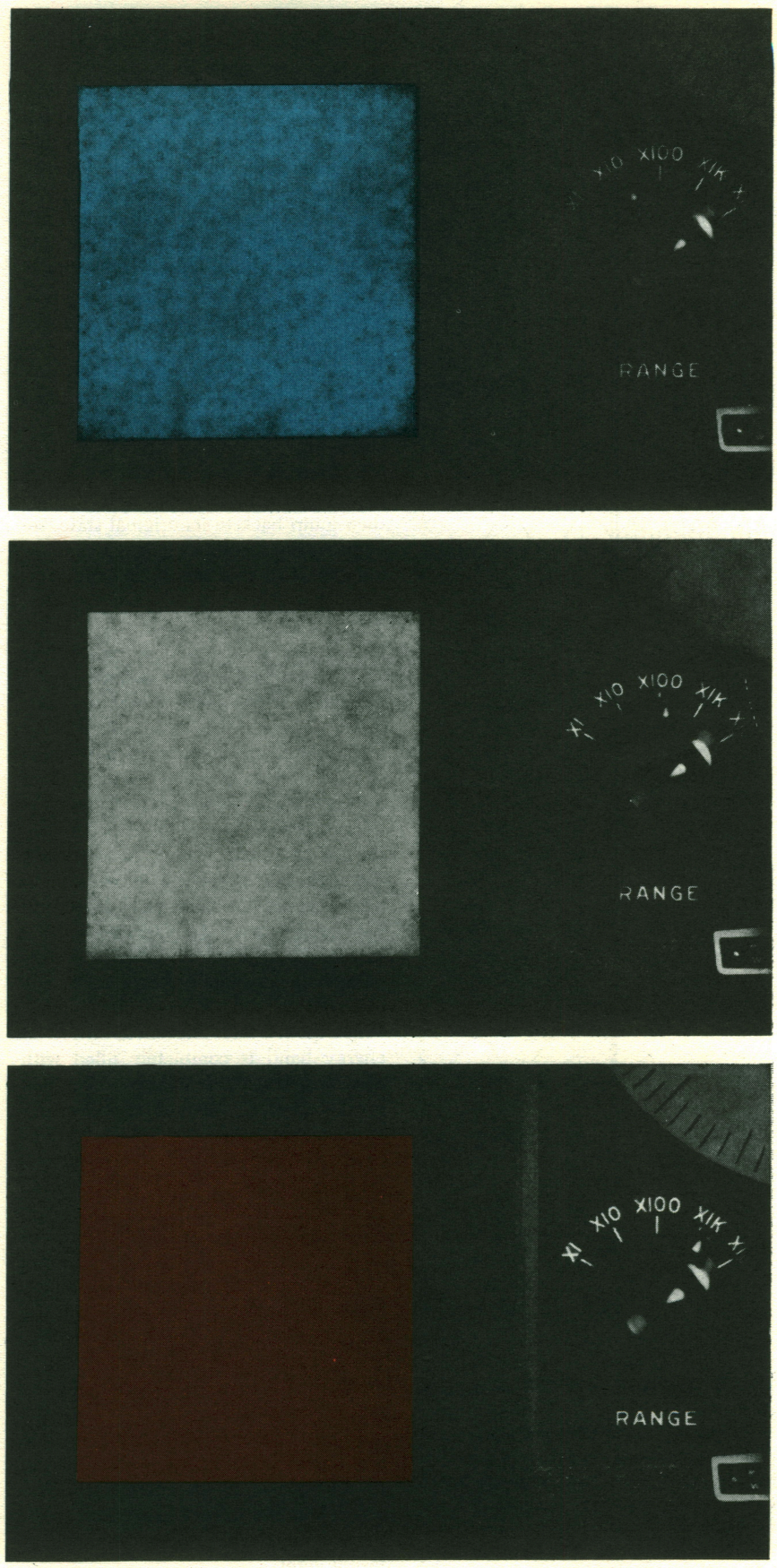
EXPERIMENTAL ILLUMINATING PANEL is seen from the front and side. The phosphor of the panel is embedded in a thin layer of nonconducting material. In back of this layer is a thin layer of opaque conducting material. In front of it is a film of conducting material on glass. The alternating voltage which causes the phosphor to glow is imposed across the conducting layers.

harsh. Night will be turned into day by curtains of light at our windows—draperies glowing with the golden shimmer of sunlight.

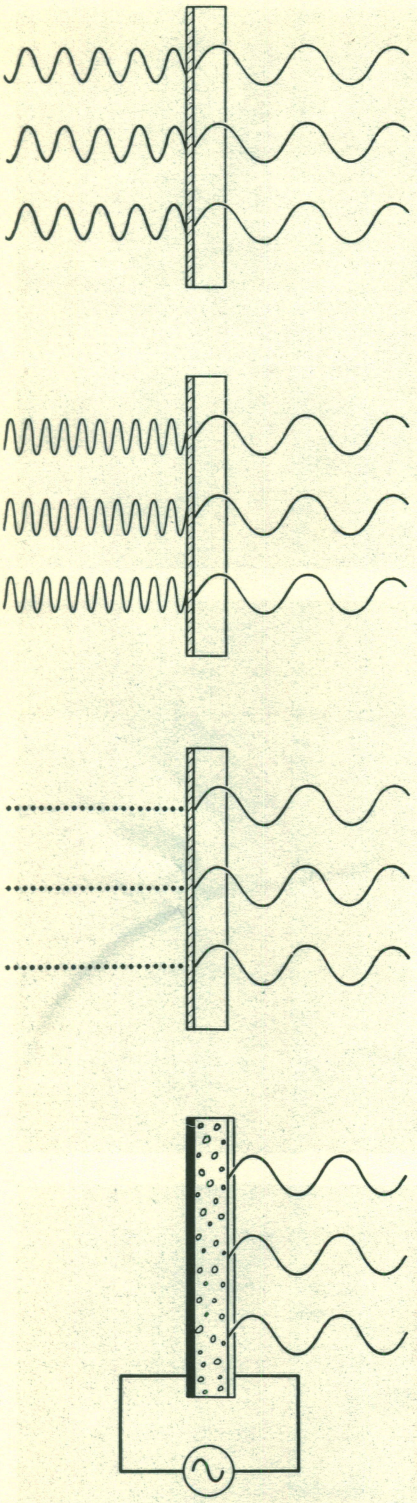
These, however, are only the more glamorous aspects of the phenomenon which is the subject of this article. Electroluminescence promises to revolutionize not only illumination but also techniques of picture-making. It can transform invisible radiations—ultraviolet, X-rays, cathode rays—into visible light. It may therefore improve X-ray photography and television, and introduce entirely new ways of forming pictures. But fully as interesting as its technological possibilities is the phenomenon itself. Electroluminescence is a new method of generating light. As such it gives us a new outlook on the behavior of energy and matter, in a realm which has recently become a cornucopia of useful and fundamental information—solid-state physics.

In a broad sense electroluminescence is not basically different from the luminescence we see in a fluorescent lamp, a fluoroscope or a television (cathode-ray) picture tube. In all of these devices the light is produced by exciting a phosphor. The difference among them lies in the agent used for excitation. In a fluorescent lamp the phosphor is excited by ultraviolet rays, produced in the tube by a gas discharge; in a fluoroscopic screen it is excited by X-rays; in a cathode-ray tube, by a beam of high-speed electrons. In the case of electroluminescence, the exciting agent is an alternating electric field. The phosphor, embedded in a thin layer of nonconducting material, is sandwiched between two layers of a material that conducts electricity. When an alternating voltage is applied to these outer layers (electrodes), it sets up an alternating electric field across the phosphor layer and causes the phosphor to emit light. From a practical point of view, the most important feature of this system is that it frees us from the confines of a tube or bulb in producing light. We can make light-emitting surfaces of any size or shape. Moreover, our "two-dimensional lamp" can be almost as thin as we please. The phosphor layer is only a few thousandths of an inch thick, and the outer layers of the sandwich can be fine wire meshes or films of a conducting substance (*e.g.*, tin oxide).

The fact that light could be generated by this method was discovered in 1936 by a Frenchman named George



COLOR OF PANEL CHANGES with frequency. Here the luminescent layer consists of two phosphors, one green and one red. The green phosphor is brighter at low frequencies; the



FOUR PHOSPHOR DEVICES are depicted schematically. In the fluorescent lamp (*top*) the phosphor (*hatched layer*) converts ultraviolet radiation (*wavy lines at left*) into light (*wavy lines at right*). In the fluoroscope (*second from top*) it converts X-rays into light. In the cathode-ray tube (*third*) it converts high-speed electrons (*dots*) into light. In the electroluminescent illuminating panel (*bottom*), the phosphor (*particles embedded in middle layer*) converts an alternating current (*wave symbol*) into light.

Destriau effect. He placed some zinc sulfide phosphors in an intense alternating field and made them glow—but so feebly that the light could be seen only in a dark room by eyes adapted to the darkness. The idea that phosphors could be excited by an electric field met with considerable doubt at first, but since 1950 Destriau's discovery has been followed up by intensive research, not only because it promises a new form of lighting but also because it is yielding new information about phosphors and the solid state.

The key to luminescence is the propensity of electrons in atoms to jump from one energy state to another. Upon absorbing a quantum of energy from some outside source, an electron jumps to a higher, or "excited," state. It may then jump back to its original state, reemitting the absorbed energy. In a phosphor, part of this energy is emitted as light. But the process is complex, and certain conditions must be met to make the electron jumps produce light rather than merely heat or other radiations.

Here is a phosphor crystal, say zinc sulfide. Since its closely packed atoms interact with one another, we must think of its electrons as occupying a band of energy levels, instead of the single, sharply defined energy level of an electron in an isolated atom. Nevertheless, just as a single electron in an atom is permitted only certain energy levels and is forbidden any intermediate energies, so there is a forbidden band of energy values which cannot be occupied by any electrons of the zinc or sulfur atoms. When the crystal is unexcited, the lowest energy band is completely filled with electrons. If exciting energy is supplied to the crystal, some of the electrons will jump from this band across the forbidden band just above it into a permissible higher band. Now if an electron jumps back to the lowest band, it will emit energy—but not in the form of light. The quantum of energy required for a jump from one level to another depends on the width of the gap, and the size of the quantum determines the frequency, or wavelength, of the radiation emitted: the bigger the quantum, the higher the frequency. In this case the gap across the forbidden band is so wide that an electron jumping back to the lower band emits its energy at a frequency in the ultraviolet region rather than in the lower-frequency region of visible light.

But we can narrow the gap. Suppose we insert a new rung within the forbidden zone to shorten the step for the jumping electrons. We can accomplish this by introducing a few copper atoms into the zinc sulfide crystal. An energy level permissible to copper's electrons lies within the band forbidden to those of zinc and sulfur. If a copper electron is excited to a higher energy level, it leaves a vacancy which can be filled by an electron dropping from the higher band. The drop to this level is short enough—that is, the quantum is of the right size—to produce emission of light. The electron berths provided by the copper atoms are therefore called luminescence centers.

There are other holes, within the forbidden band and close to the higher energy band, into which electrons may fall. They are called traps, and are created by imperfections in the crystal or by chlorine atoms, which are introduced to control the number of copper atoms dissolved in the crystal. Electrons falling into traps generate only heat, but they are easily excited out of the traps and then can fall into empty luminescence centers, producing light.

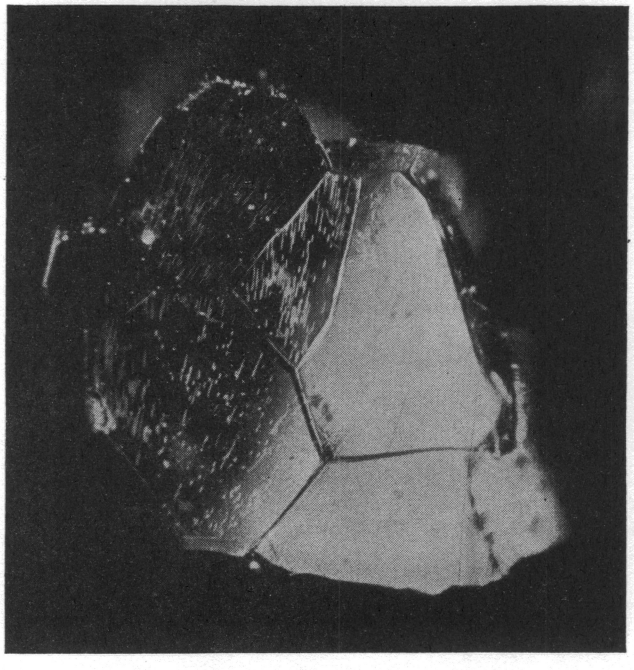
The foregoing describes the mechanism of the more familiar types of luminescence, such as fluorescence. The ultraviolet rays in a fluorescent tube excite electrons contained in the phosphor to the higher permitted energy band, and the excited electrons then fall into empty luminescence centers. When we come to electroluminescence, the process is more indirect. The alternating electric field cannot kick electrons out of the centers directly. What it does is to accelerate free electrons, and these accelerated particles then knock electrons out of the luminescence centers, creating vacancies into which electrons can fall with emission of light. In practice, if the method is to produce much light, the phosphor has to be specially treated to increase the effectiveness of the electric field. Small particles of copper sulfide are introduced into the phosphor. Because copper sulfide is a good conductor, each of these particles concentrates and intensifies the electric field around it, and so enhances the acceleration of electrons.

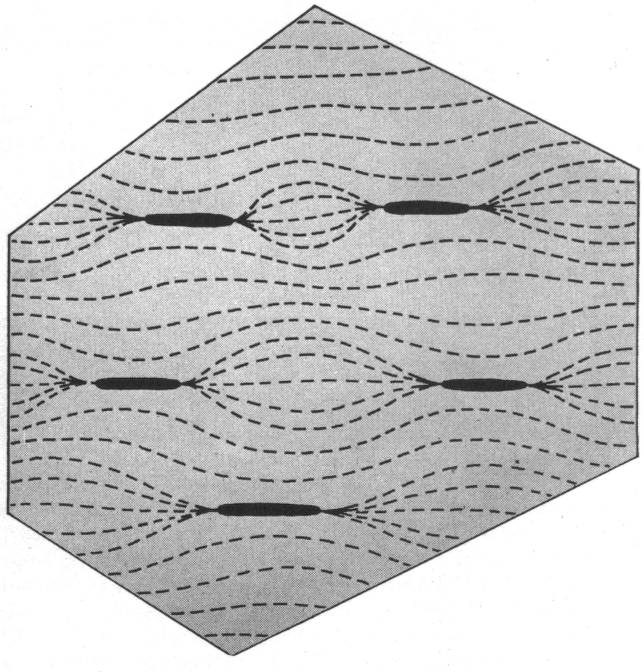
We get something of a picture of how the process works by setting up a mechanical analogy. Let us take a board pitted with holes like a Chinese checkerboard: deep holes represent luminescence centers and much shallower ones represent traps. Using marbles as electrons, we fill all the luminescence centers and some of the traps with electrons. The board is mounted on a fulcrum so that it

EXPERIMENTAL ROOM at the Bloomfield, N. J., plant of the Westinghouse Electric Corporation is illuminated with electroluminescent panels. The panels were made with zinc sulfide activated with copper. They operate at 400 volts and 3,000 cycles.

tilts from one side to the other like a seesaw: this represents the alternating electric field [*see drawings on page 45*].

Now suppose we look at one side of the board as it is tilted down. As the steepness of the tilt increases, marbles begin to roll out of the shallow traps; some hit marbles in luminescence centers and knock them out; soon there is an avalanche of marbles rolling down the surface of the board (representing the higher energy band). Then, after the board reaches its steepest tilt and starts back up again, the avalanche slows down. When the board returns to the horizontal position, the marbles stop rolling. They fall into traps, because there are no empty luminescence centers out near the periphery where they are concentrated. Many of the centers nearer the middle of the board are, however,





CRYSTALS OF CADMIUM SULFIDE, enlarged 200 times in the photograph at left, are shot through with needle-like dislocations of their crystal lattices. The diagram at right shows a crystal of zinc sulfide containing particles of copper sulfide in similar dislocations. Because copper sulfide is a good conductor, the particles distort and intensify an electric field (*broken lines*) around them.

unoccupied. Now the side of the board that we are watching begins to tilt upward. The marbles roll out of the traps and back toward the empty centers. They drop into these holes. The cycle is completed when the board again comes back to the horizontal position.

Meanwhile on the other half of the board the same thing has happened, but one half-cycle out of phase. Thus while luminescence centers are being emptied on one side of the board they are being filled on the other.

This is what happens around each local intensification of the electric field in a phosphor. The field, though not strong enough to dislodge electrons from luminescence centers, can free electrons from the traps and so start an avalanche. Once started, the avalanche excites many of the electrons out of the centers by means of collisions. It slows down as it reaches areas of low field strength. The electrons then fill nearby traps, only to be liberated again by the reverse build-up of the alternating field, which accelerates them back toward the empty centers. When electrons drop into the centers, they emit light.

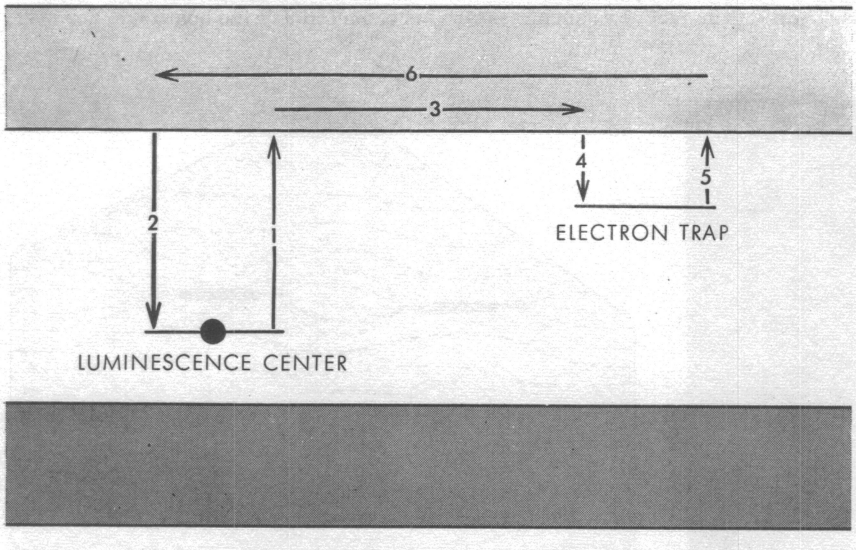
The main problem in electroluminescence is to get enough output of light from the phosphor. There are two ways to step up its brightness: increase the voltage (*i.e.*, strengthen the electric field) or speed up the field's oscillating frequency. If we strengthen the field, we generate more light emission by emptying and refilling more luminescence centers in each cycle; if we increase the frequency (rock the board faster), we get the same result by emptying and refilling the centers more rapidly. But there are limits to both stratagems. Too strong a field will break down the insulating property of the phosphor layer; too short a cycle will not give the electrons time enough to emerge from their traps.

The highest brightness yet produced—achieved by exciting a green phosphor with a field at 20,000 cycles per second—is 2,500 lumens per square foot of phosphor area. This is brighter than a standard 40-watt fluorescent lamp. But it takes an inordinate amount of electric power, because the efficiency of the electroluminescent process is low. At 20,000 cycles per second electroluminescence yields only about one lumen per watt of applied power, whereas a fluorescent lamp gives 65 lumens per watt, and even an incandescent electric-light bulb (of 100 watts) yields 16 lumens per watt.

The reason for the low efficiency of electroluminescence is that the avalanching electrons spend most of their energy in collisions with atoms in the crystal: only a minority knock electrons out of luminescence centers. It has been found that the process behaves most efficiently when the applied electricity has a potential of a few hundred volts and a frequency of a few hundred cycles per second. The highest efficiency obtained so far is 12 lumens per watt. The aim of the workers on this problem is to raise the efficiency to about that of diffused fluorescent lighting—namely, about 30 lumens per watt.

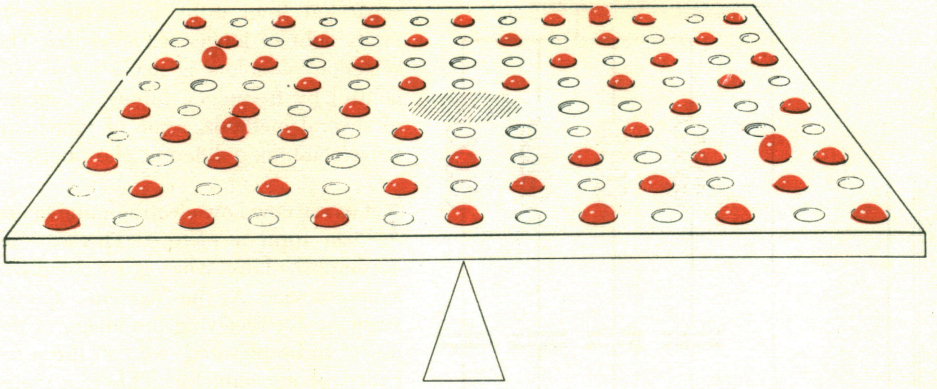
Until more effective materials are developed, electroluminescent lighting will require alternating electricity of considerably higher frequency than the 60-cycle current now supplied by power lines. For houses, small converters using transistors may serve to convert this current to the necessary frequencies. In a large office building it would be quite feasible to install a generator which would deliver power at frequencies around 1,000 cycles per second. The cost of such an installation would be offset by a great saving in the cubage of the building, because it would need only very thin ceilings, in place of the space now required for lamp fixtures. Whereas recessed fluorescent lamps, for instance, need a depth of 14 inches, electroluminescence would thin the ceiling down to less than one inch.

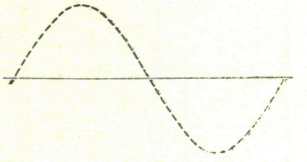
The fact that electroluminescent surfaces can take any size or shape provides an endless list of possibilities. Light might be built into walls, doors, stairs, balustrades, domes or any other elements of a building. It could be built into furniture and even into draperies, because the luminescent sheets can be made as flexible as cloth. And the color of the light could be changed instantly by tuning the applied electricity to a different frequency. The available colors depend on the substances introduced into the phosphor to provide luminescence centers. Copper gives blue or green. Manganese, whose electrons occupy an energy level closer to the upper energy band of the phosphor (*i.e.*, are

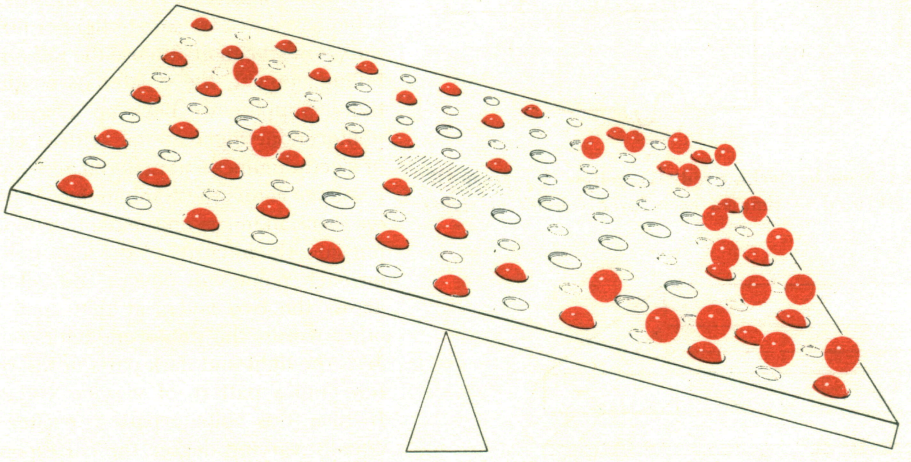


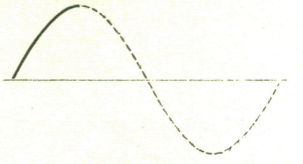
ENERGY BANDS of a zinc sulfide crystal are schematically depicted. At bottom is the band occupied by unexcited electrons; at top, the band occupied by excited electrons. Between the two is a "forbidden" band which cannot be occupied by electrons in a pure crystal. If an electron in such a crystal jumps from the lower band to the upper and falls back again, it may emit ultraviolet radiation or simply radiate heat. If copper atoms are introduced into the crystal, they form a luminescence center whose energy level is in the forbidden band. If an electron jumps from this level (1) and falls back again (2), it emits light. The electron can also wander through the crystal (3) and fall into an electron trap (4). Such a trap is created by an imperfection in the crystal or by chlorine atoms which are introduced to control the number of copper atoms. The electrons are easily dislodged from the trap (5) and can then fall back to the level of the luminescence center (6 *and* 2).

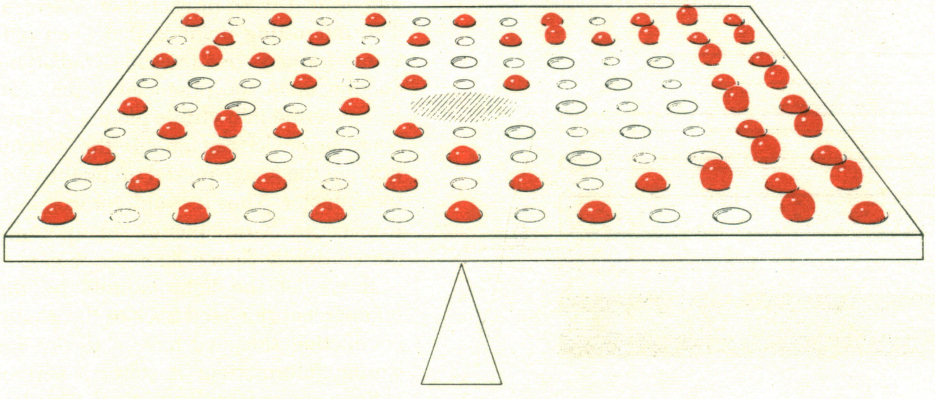
MECHANICAL ANALOGY discussed in the text of this article is depicted on the opposite page. The colored balls are electrons; the deep holes, luminescence centers; the shallow holes, electron traps. The hatched area in the center represents the copper sulfide introduced into the zinc sulfide crystal to intensify the electric field. The tilting of the board is an analogy for the alternation of the voltage, which is also represented by the curves at the far right.

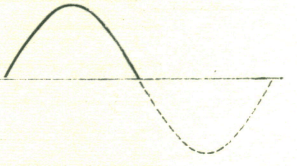


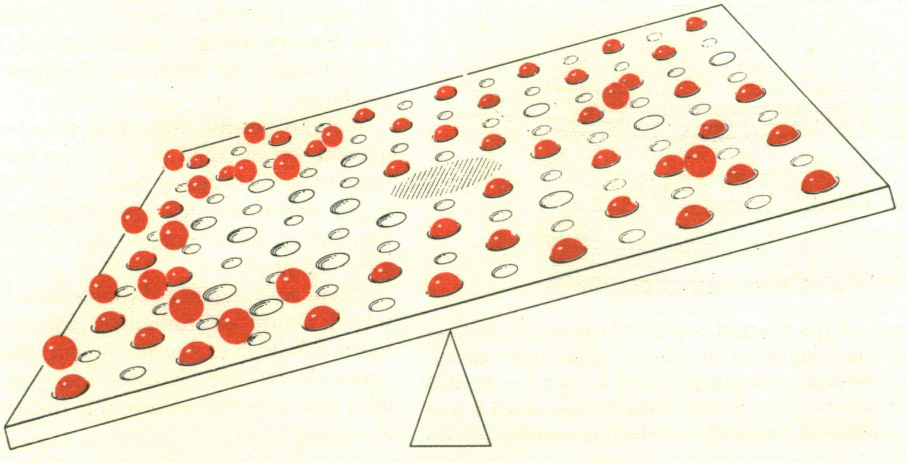


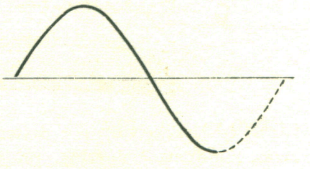


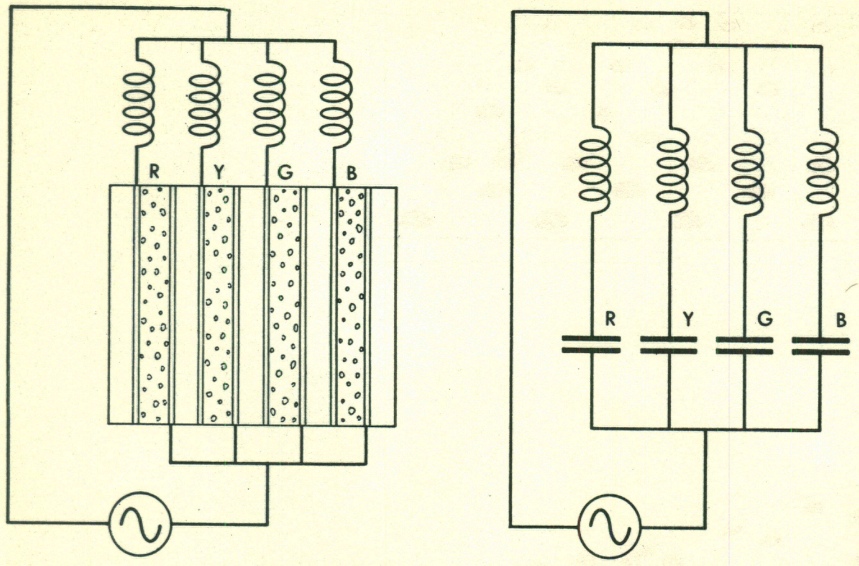




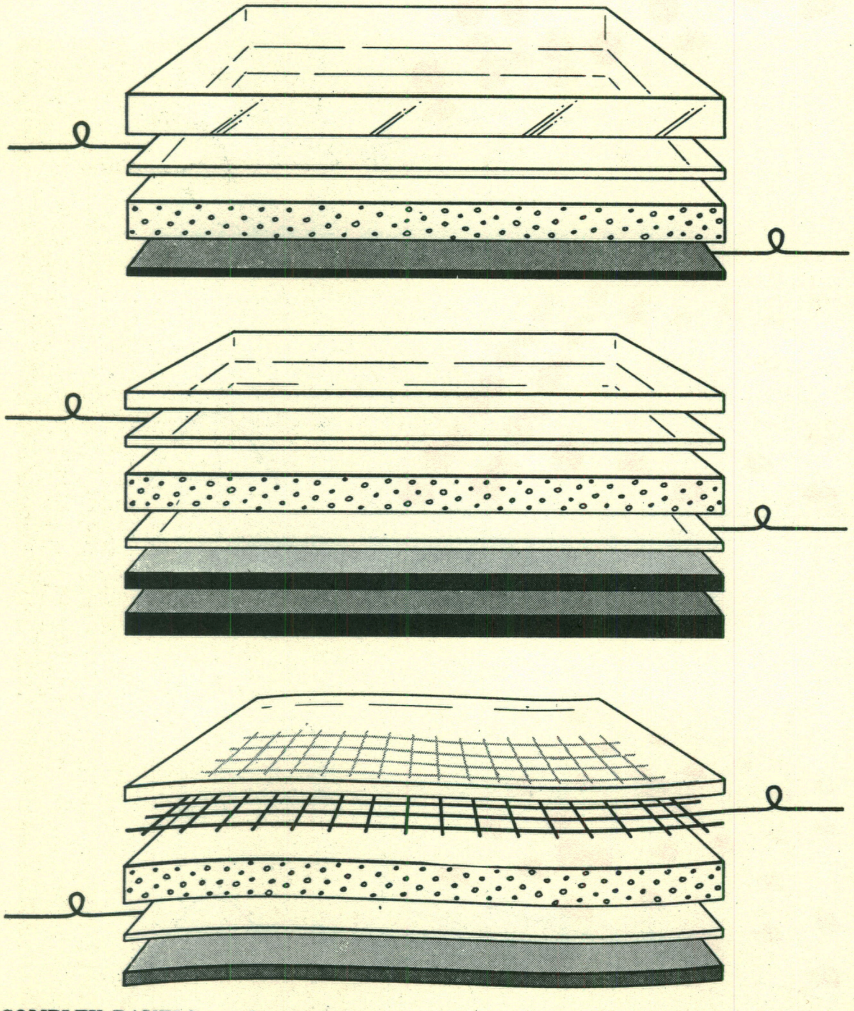








MULTICOLORED PANEL of one type is made by stacking red (R), yellow (Y), green (G) and blue (B) phosphors. Inductors are used to tune in each layer (*circuit at right*).



COMPLEX PANELS are dissected. Layers of the panel at top are, from top to bottom: glass, conducting coating, phosphor particles suspended in plastic, conducting coating. Layers of the cell in middle are: plastic, conducting coating, phosphor particles embedded in low-melting-point glass, reflecting enamel, metal base. Layers of the flexible panel at bottom are: plastic, wire mesh, phosphor embedded in plastic, conducting coating, plastic.

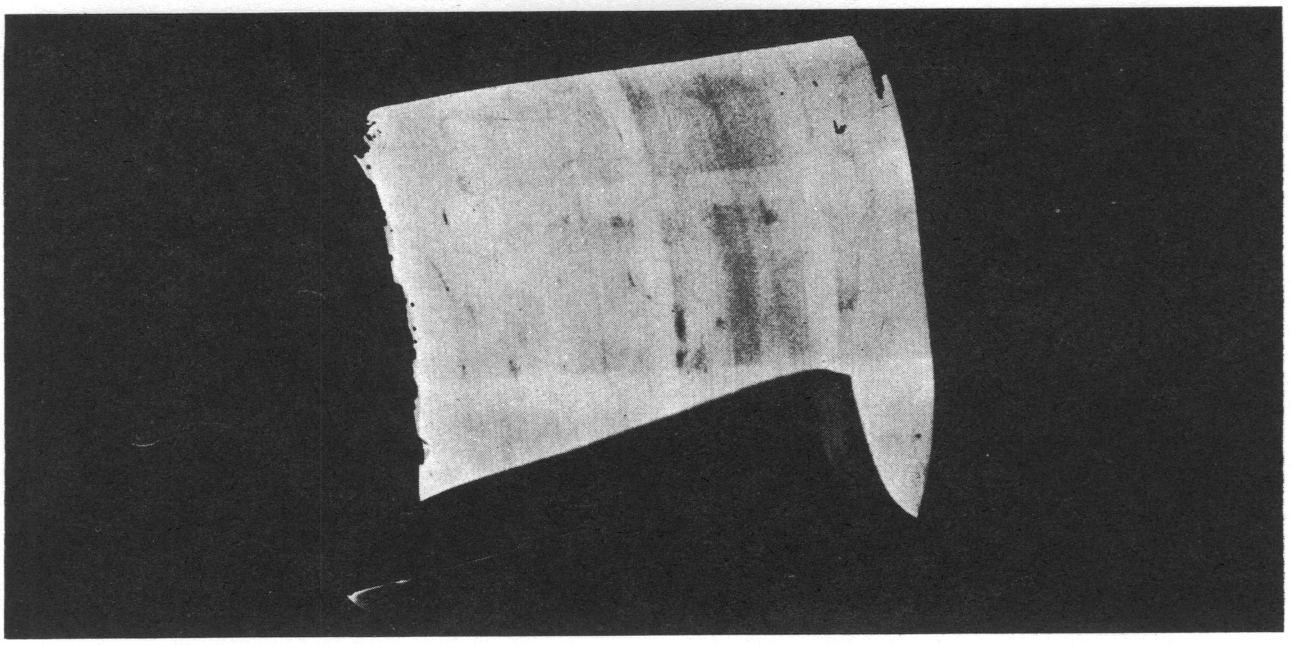
separated from it by a shorter gap), emits light of longer wavelengths. The selection of colors is made subject to control by frequency tuning by means of several methods, some of which involve combining different phosphors.

Let us see now how electroluminescence can form a picture. This can be accomplished by what is essentially a simple device. As the "camera"—the instrument for receiving the image of the object to be pictured—we can use a so-called photoconductor. This is a material whose ability to conduct electricity is increased by exposure to light or other radiation—the more intense the radiation falling upon it, the greater its conductivity. Suppose we back up a layer of photoconducting material with a layer of electroluminescent material and apply a voltage across the combination. If now we focus an image on the photoconducting side, the intensity of the light falling on each point will govern the voltage across the two layers at that spot. In other words, the photoconductor translates the light and dark parts of the picture into a pattern of varying voltage. In turn, this voltage pattern excites in equally varying degree the corresponding points in the phosphor on the other side of the sheet. The luminescent phosphor therefore displays the original image, as if it were projected on a screen. The interesting point is that even patterns formed by invisible radiations (acting upon the photoconductor) can be converted into visible pictures. Moreover, the device can amplify the "brightness" of the image picked up by the photoconductor. Thus it could, for example, display an X-ray picture many times more brightly than a fluoroscope can.

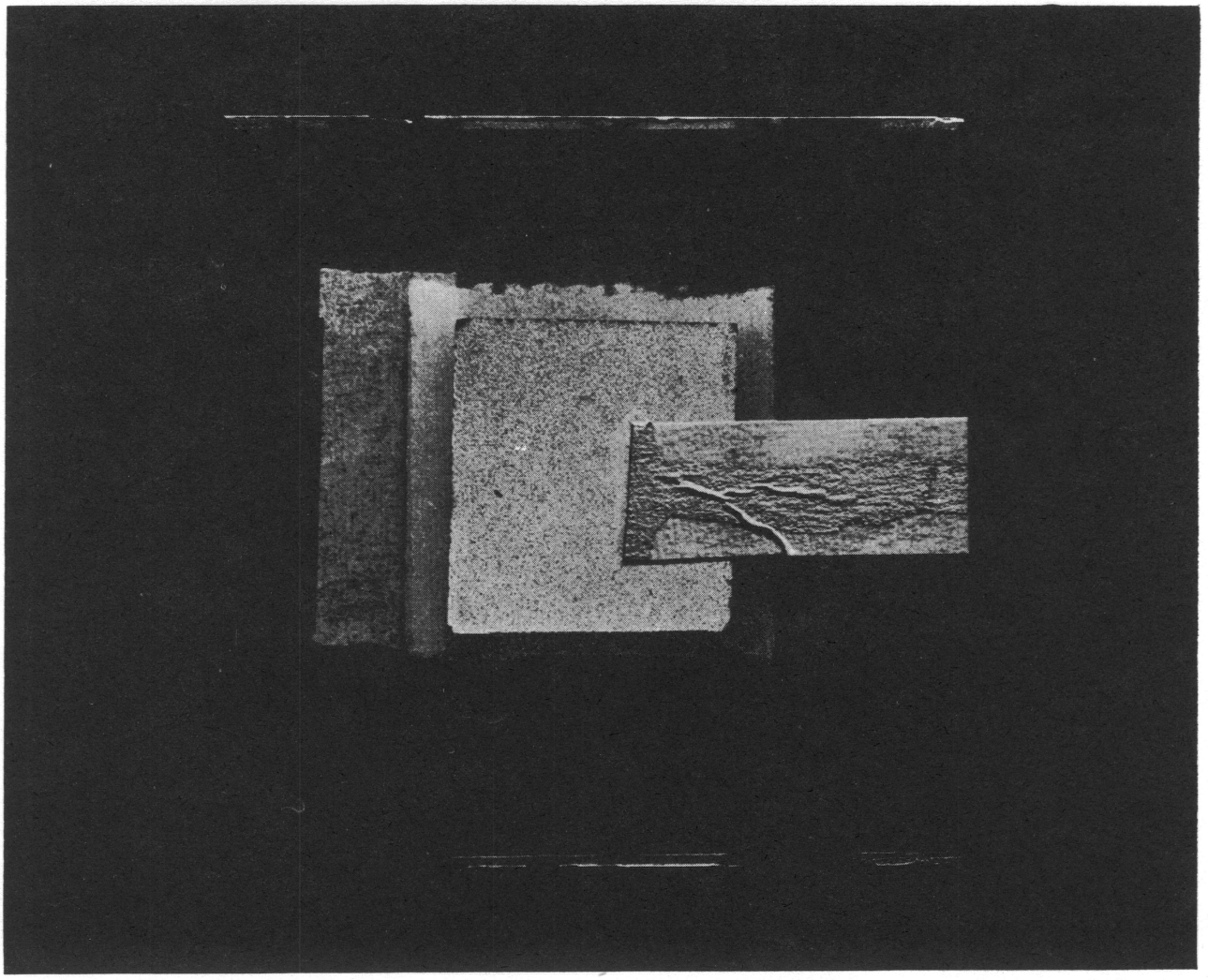
If we let the light emitted by the luminescent side feed back to the photoconducting side, we have a device for storing information: it stores a certain voltage even after the original stimulating signal has been removed. This compact form of storage could be useful for incorporation in electronic computing machines.

It seems possible that an electroluminescent screen could perform the functions of a cathode-ray tube; if so, we might eventually have television sets thin enough to be hung on the wall like a framed picture.

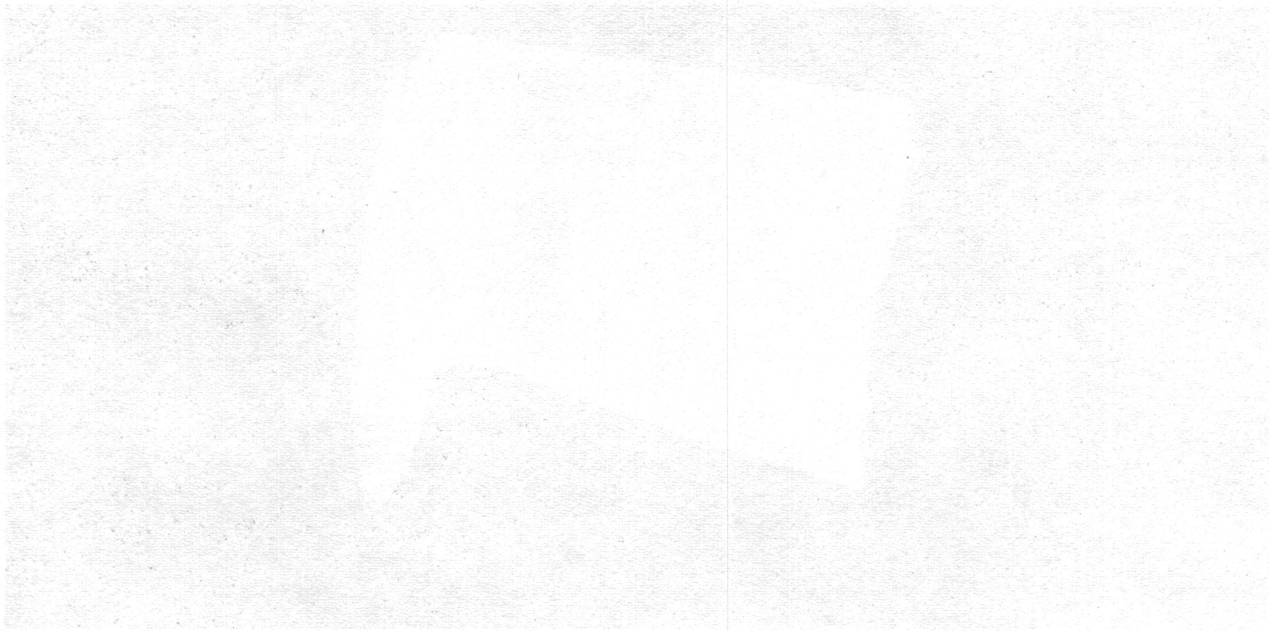
There are a number of problems to be solved before electroluminescence enters our daily lives, but the research laboratories working on them hope that, with luck, they will be solved in the next few years.

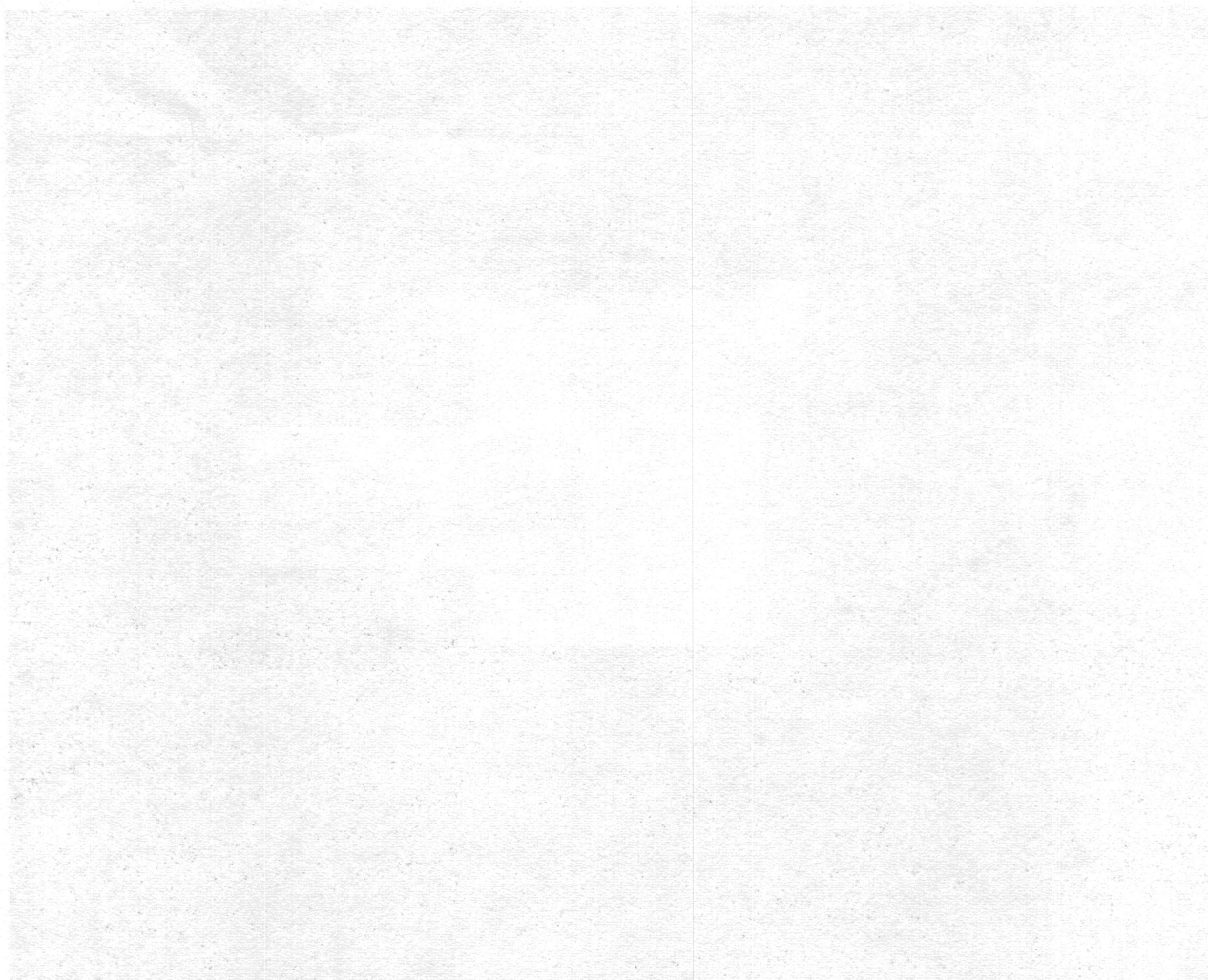


FLEXIBLE PANEL in this photograph was made by spraying a layer of phosphor suspended in a nonconducting material on a screen with 200 meshes to the inch and covering it with a layer of vaporized aluminum. Panel operates at 110 volts and 4,000 cycles.



TEST PANEL is built up on glass. The oblong at right is the connection of the square electrode beneath it. The larger square beneath the electrode is phosphor in plastic. The oblong at left is the connection of the other electrode, which is not visible.





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